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U.S. DEPARTMENT OF ENERGY
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DOE/NASA AUTOMOTIVE STIRLING ENGINE PROJECT - OVERVIEW 1986

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E-3098

SUMMARY

The DOE/NASA Automotive Stirling Engine Project is reviewed and its technical progress and status are presented. Key technologies in materials, seals, and piston rings are progressing well. Seven first-generation engines, and modifications thereto, have accumulated over 15 000 hr of test time, including 1100 hr of in-vehicle testing. Results indicate good progress toward the program goals. The first second-generation engine is now undergoing initial testing. It is expected that the program goal of a 30-percent improvement in fuel economy will be achieved in tests of a second-generation engine in a Celebrity vehicle.

BACKGROUND AND OBJECTIVES

The Automotive Heat Engine Program was begun by the Environmental Protection Agency (EPA) in 1971 with the initial objective of developing alternative automotive heat engines with significantly reduced exhaust emissions. In 1973 the objectives of improved fuel economy and multifuel capability were added. In 1975 the Stirling engine was selected as one of the promising candidates for detailed investigation.

With the formation of the Energy Research and Development Agency (ERDA) in 1978 the EPA automotive propulsion system activities were transferred to ERDA, and additional emphasis was placed on developing alternative propulsion systems with substantially improved fuel economy and adaptability to various fuels that at the same time would meet the legislated emission standards. In this revised program the NASA Lewis Research Center was assigned project management responsibility for implementing the Automotive Heat Engine Program. This relationship was continued when the transportation conservation activities of ERDA were transferred to the newly formed Department of Energy (DOE) and continues today. The Automotive Stirling Engine (ASE) Program prior to 1983 is described in detail in reference 1.

The "Automotive Propulsion Research and Development Act of 1978" (Title III, P.L. 95-238) specifically directed the Department of Energy to "establish and conduct new projects and accelerate existing projects which may contribute to the development of advanced automobile propulsion systems and give priority attention to the development of advanced propulsion systems, with appropriate attention to those advanced propulsion systems which are flexible in the type of fuel used." Consistent with these and other directives of P.L. 95-238 and with specific guidelines provided by the DOE Office of Transportation Programs, the goals of the ASE Program are to develop and verify the technology base necessary to meet the following propulsion system objectives and to provide confidence in that technology base by verifying the technology in appropriate test-bed engines:

(1) At least a 30-percent improvement in fuel economy (miles per gallon) over a production vehicle of the same class and performance powered by conventional spark ignition engines (based on equal heating value content of the fuel used)

(2) Emission levels that meet or exceed the most stringent Federal research standards; 0.4/3.4/0.4/0.2 g/mile of HC/CO/NO_x/particulates

(3) The ability to use a broad range of liquid fuels derived from crude oil as well as synthetic fuels from coal, oil shale, and other sources

(4) Suitability for cost-competitive mass production

The specific technology objectives are

(1) To develop metal alloys low in strategic element (particularly cobalt) content

(2) To develop the technology for seals with leakage, friction, and life characteristics suitable for the application

(3) To develop the technology necessary for low-emission combustion systems

(4) To develop component technologies required to reduce engine cost and weight and to improve engine performance and life in support of the program objectives

(5) To identify and evaluate advanced concepts, not expected to mature by 1987, that may significantly affect life, cost, or performance

PROJECT DESCRIPTION

The basic structure of the current project is shown in figure 1. The primary technology development effort is being conducted by a team consisting of Mechanical Technology Inc. (MTI) and United Stirling of Sweden (USAB). This DOE-funded, NASA-contracted effort began on March 22, 1978. MTI is responsible for overall contract management, development of component and subsystem technology, and transfer of Stirling engine technology to the United States. USAB is responsible for in-engine technology verification and for providing the initial base of Stirling technology to the program.

This contract effort has been focused on a reference engine system design (RESD) intended to represent the best engine that could be designed to meet the program goals using the technologies reasonably expected to be developed over the life of the program. Two generations of engines were planned toward the development of the reference engine. The Mod I engine used technology available early in the program and was a first step toward the reference engine design. The Mod II engine was then planned to incorporate all of the technologies for the reference engine design and would in theory be an experimental version of the RESD. In 1981, at DOE direction, the Mod II engine was deleted from the program, and emphasis was placed on demonstrating the technology in upgraded versions of the Mod I engine. However, in accordance with Congressional direction, the Mod II engine was restored to the program in 1984.

In addition to overall management of the ASE Project Lewis has carried out, through both in-house and contracted activities, a number of separate research and technology efforts. These efforts have supported the technology verification goal and identified and evaluated more advanced concepts. These advanced concepts are not expected to mature in the life of the program but may significantly affect life, cost, or performance. In-house testing has been done on four engines: the General Motors GPU-3 (ref. 2), the USAB P-40 (ref.3), the N.V. Philips Advenco, and the Mod I engine. Engine performance has been mapped to provide data for computer code validation. Specific technology evaluations have included jet impingement heat transfer tests in the GPU-3, hydrogen permeation tests in the P-40, and variable-stroke performance tests in the Advenco engine. Testing of a Mod I engine was recently begun. Extensive contracted and in-house work has been done on materials, seals, controls, and Stirling engine computer codes.

TECHNICAL PROGRESS AND STATUS

Mod I Engines

The Mod I engine (fig. 2) is a four-cylinder, double-acting engine with dual crankshafts. It incorporates one canister type of regenerator/cooler per cylinder. As the first engine designed in the program it was designed for a heater head temperature of 720 °C rather than the 820 °C planned for the RESD. Considerable materials selection and evaluation efforts were required to make the 820 °C level practical.

When the Mod II engine was temporarily dropped from the program, we planned to evaluate as many as possible of the Mod II technology advances in upgraded versions of the Mod I engine. Some of these improvements are shown in a cross section of the upgraded Mod I (fig. 3).

Seven experimental Mod I and upgraded Mod I engines have been built and tested in the project and have now accumulated over 15 000 hr of test time. This includes over 1400 miles and 1100 hr of testing in two vehicles. Test time per year is plotted in figure 4. These test hours include several endurance tests of over 1000 and 2000 hr duration at heater head temperature of both 720° C (original Mod I design) and 820 °C (Mod II design temperature incorporated in upgraded Mod I engines) (see table I). These endurance hours were generally run on a duty cycle simulating the EPA urban and highway driving cycle (fig. 5), with the engines operating in essentially continuous transient operation.

Before 1981, in the early days of the ASE Program, five USAB P-40 engines were operated for about 1000 hr with a mean time between failure (MTBF) of less than 10 hr. Later, before 1983, four Mod I engines were operated for nearly 2000 hr, with MTBF's ranging from 26 to 121 hr for operating times of 238 to 701 hr. With over 15 000 hr of Mod I and upgraded Mod I engine operation and experience and an effective quality assurance program to identify problem areas, the MTBF's have made a dramatic improvement (table II).

Industry Test and Evaluation Program

An Industry Test and Evaluation Program (ITEP) was begun in 1983 to obtain an independent evaluation of the Mod I engines by engine and automobile manufacturers. The Government offered to loan Mod I engines to industry participants with the participants conducting the tests and evaluations at their own expense. Two companies accepted the Government offer and tested Mod I engines in the summer and fall of 1984.

The first participant, General Motors Research Laboratories (GMRL) in Warren, Michigan, requested that the engine be installed in a vehicle to allow a comparison with an existing vehicle system. The engine was installed in a 1981 Spirit and delivered to GM on April 24, 1984. GMRL personnel conducted a three-phase test program that included

(1) Emissions and mileage tests in a constant-volume sample (CVS) test facility

(2) Cooling system evaluation in a wind tunnel

(3) Driver evaluation on a test track

The ASE Mod I engine installed in the Spirit vehicle successfully completed 54.7 hr of operation and 1062 miles at the GMRL facilities. Results of these tests were documented in a GMRL report (ref. 4). The following highlights of these results include quotes from the GMRL report:

(1) No major hardware failures - reliability "was remarkable during the 54.7 hr of testing"

(2) Met current Federal emission standards with "a comfortable margin" without a catalytic converter

(3) Acceleration times considered sluggish by GMRL personnel and "suffered severely at highway speeds"

(4) "Passed standard cooling tests with ease" (oversized radiator)

(5) High-idle fuel flow and the cold-start penalty identified as major contributors to mileage shortfall on the urban cycle

The second industry participant, Deere & Company, evaluated an ASE Mod I engine in a Deere test cell in Waterloo, Iowa, in September and October of 1984. The engine was operated for 37 hr with no major hardware failures. The engine was started and operated on gasoline, diesel, and JP-4 fuels without changes to the control or combustor systems. With diesel fuel a significant ignition delay resulted in sooting of the air preheater. Limited noise data were taken although the test cell was not equipped for taking quantitative acoustic data. Qualitative results indicated that the Stirling at full power made no more noise than a diesel engine at idle. Analysis of the acoustic data revealed that the dominant frequency was associated with the gearing of the two-shaft drive system. (This source of noise is eliminated with the Mod II single-shaft drive arrangement.) Tests were run at various heater and cooler temperatures with the expected effects on power and efficiency. Test results and comparisons with diesel engines are described in detail in a Deere & Company report (ref. 5).

Government and Industry Participation Program

A follow-on to the ITEP program was begun in 1985 when some of the Mod I and upgraded Mod I engines were no longer needed in the program. These surplus engines are being made available for additional evaluation and testing by industry and other Government agencies in the Government and Industry Participation Program (GIPP). The GIPP ground rules allow evaluation and testing for both automotive and nonautomotive applications. However, no program resources are available to support these evaluations so that participants must provide any resources required for training, spare parts, modifications required for the application, etc.

Two GIPP activities are currently under way. The first is the Ft. Belvoir engine-generator set program. In this effort an upgraded Mod I Stirling engine was loaned to the U.S. Army, Ft. Belvoir. They contracted with MTI and Tiernay Turbines of Phoenix, Arizona, to make the necessary modifications to replace the diesel engine in a standard Army engine-generator set with the Mod I Stirling engine. MTI made the appropriate control system modifications, and Tiernay did the installation work. The resulting 25-kW Stirling-generator set is undergoing a 500-hr test by the U.S. Army to evaluate the technology status of the Stirling engine for this application.

The second GIPP activity is the Stirling-Powered Air Force Van Program. In this program an upgraded Mod I Stirling engine will be installed in an Air Force multistop van, which will then be evaluated in regular service at Langley Air Force Base. A 1000-hr test period is planned, with the first 500 hr to be run with unleaded gasoline and the last 500 hr with JP-4 fuel. Additional multifuel testing is planned. The Stirling-powered van will be evaluated by Management and Equipment Evaluation Program (MEEP) personnel under Air Force Tactical Command at Langley Air Force Base. If results of this phase I evaluation are positive, a phase II evaluation will include testing at several Air Force bases under a variety of environmental conditions. Finally a phase III effort is planned that would test Mod II engines in Air Force vehicles in 1988 and 1989.

This program is being carried out as a cofunded effort with the following participation:

Management	NASA Lewis
Loan of Mod I ASE	DOE
Field testing	Air Force (MEEP) (all phases); Purolator Courier (phases II and III); Deere & Company (all phases)
Potential manufacturer	Deere & Company
ASE contractor	Mechanical Technology Inc.
Potential users	Purolator Courier; American Trucking Associations, Inc.; Air Force and other Government agencies

This van program is described more completely in reference 6.

KEY TECHNOLOGIES

At the start of the program a number of specific technology problems required resolution. These problems and the progress toward their resolution are reviewed here.

Materials

At the start of the program the heater heads (castings and tubes) of Stirling engines generally contained high-cost alloys with high content of the strategic alloy cobalt. Considerable effort has been expended in the program to identify and validate alternative alloys with acceptably low cost and low strategic material content (refs. 7 and 8).

The alloy CG-27 was identified and validated for the heater tubes. It is an iron-base alloy with low strategic alloy content and no cobalt. Its strength is comparable to that of N-155, the cobalt-containing material generally in use in Stirling engines at the start of the program. The alloy XF 818 was selected for the heater head castings. It has low strategic material content and no cobalt. Its strength, while adequate, is somewhat less than that of the cobalt alloy HS-31 that it replaces, resulting in some efficiency penalty.

Development is also being carried out on an experimental casting alloy NASAUT 4G-A1 (ref. 9). This material was originally developed as a directionally solidified alloy. It offers the potential for lower cost and improved strength but still requires some development and property determinations before its use in an engine.

The problem of hydrogen loss due to permeation through the high-temperature heater tubes has been addressed (ref. 10) by doping the hydrogen with small quantities of CO or CO_2. This reduces the permeability loss in the selected CG-27 heater tube material by two orders of magnitude and should make the permeability loss compatible with the hydrogen leakage goal of the program - hydrogen recharging no more than once every 6 months.

Reciprocating Shaft Seal

The reciprocating shaft seal on the piston rod has historically been a critical problem for the Stirling engine. Although this problem has not been fully resolved, substantial progress has been made. The USAB pumping Leningrader (PL) seal adequately controls hydrogen and oil leakage rates but has not yet demonstrated adequate and consistent life capability. (The engine life goal is 3500 hr.) A number of seals have operated for over 2000 hr in Mod I engines on a simulated CVS duty cycle without failure, but occasional seal failures still occur after 100 to several hundred hours. Although there is no conclusive evidence, it is believed that much of the problem in obtaining consistent long seal life may be due to difficulties in aligning the seal housing and the piston rods. Stirling Thermal Motors (STM) of Ann Arbor, Michigan, is exploring a compliant seal mounting arrangement. Some consideration has been given to developing a bellows type of rod seal. However, at this point it is believed that with further development the PL seal will be adequate for the 3500-hr life goal of the automobile application. For longer applications (10 000 to 50 000 hr), it may be necessary to develop a positive seal, such as can be provided with a bellows seal design.

Piston Rings

Piston ring performance and life are of course critical to the Stirling engine. The piston rings generally are made from Teflon-based materials. Wear rates depend on load, speed, and temperature. The design approach then is to control the ring loading, provide wear compensation, and limit piston ring and cylinder wall temperatures. To this point the piston rings appear to be working well and life data are very promising. Several engine endurance tests of 1000 and 2000 hr have been completed without ring failures. Generally ring failures are secondary failures, usually a result of oil leakage into the engine. (Oil decomposition products tend to foul the rings, causing excessive leakage and unbalanced cycle pressures).

Ceramic Preheater

The preheater in the Mod I engine is a large ring of about 1000 welded metal plates. Since this is one of the significant high-cost parts in the engine, an effort was begun to develop a ceramic preheater. MTI subcontracted with Coors of Golden, Colorado, for this development. The design being pursued employs some 10 individual ceramic modules. Early in this activity a module was successfully fabricated and thermally cycled. It showed acceptable leakage with no increase in leakage due to the thermal cycling. However, considerable difficulty has been experienced in trying to reproduce this result consistently while meeting the dimensional requirements of the design. Dimensional changes are being explored as a means for relieving the fabrication difficulties.

Alternative Fuel Tests

A key advantage of the external combustion Stirling engine is the ability to use a variety of liquid fuels. This capability has not been strongly emphasized to this point in the program as emphasis has been placed first on achieving the basic performance goals. However, steady-state alternative fuel tests were conducted with a Mod I combustor in a bench test rig. These tests were run with gasoline, diesel fuel, and a 50-50 mixture of diesel and naphtha fuels. Test results showed that emissions with all the fuels were well within the values that correspond to the Federal research emission standards. As indicated earlier, ignition delays were encountered in the testing at Deere & Company with diesel fuel. Additional work is now under way at MTI to ensure proper startup and transient performance with diesel fuel.

Engine Control and Auxiliaries

The basic engine control approach is a variable-pressure system, with engine pressure increased or decreased to vary power. Heater tube temperature is measured and controlled to a constant value. Substantial improvements in the controls and auxiliaries have been made during the program. The latest designs for the Mod II engine are currently being checked out on an upgraded Mod I engine in the Spirit vehicle. Control improvements are a major contributor to the improved fuel economy expected in the Mod II engine. These include reduced idle fuel flow, more effective short circuiting for rapid power reductions, an electric blower drive system, reduced control valve dead band, and digital engine and air/fuel control systems. Vehicle driveability, which is a prime function of engine response, was considered very good by GMRL when they tested the Mod I Spirit vehicle. With the additional improvements being developed for the Mod II engine, the Mod II Celebrity should display even better driveability.

MOD II AUTOMOTIVE STIRLING ENGINE

The second-generation (Mod II) engine, with the benefit of developments to date, should closely approximate the latest reference engine system design (RESD) (fig. 6). Note that the 1981 RESD had been significantly modified in 1983, before the Mod II design. The primary changes were the change to a single-shaft V-configuration, the use of annular regenerators and coolers, and the use of a ceramic preheater.

The Mod II engine (fig. 7) is a close approximation of the RESD. The primary differences are the use in Mod II of a metallic preheater (ceramic preheater development is not yet adequate), slightly larger dimensions, and about a 15 percent increase in weight. Much of the weight increase is the result of not attempting to remove all of the excess material in an experimental engine. Expected baseline performance and key features are tabulated in table III. At this time the first Mod II engine is undergoing initial dynamometer testing at MTI.

MANUFACTURING COST PROJECTIONS

A major objective of the 1983 RESD was to reduce the complexity and manufacturing cost of the basic Stirling engine and the auxiliaries and systems necessary to operate it. This RESD incorporated such recently developed technologies as a single-piece V-block, annular heater head castings, a ceramic preheater, a single crankshaft, a simplified combustor, materials to allow 820 °C operation, a lightweight piston/rod design, and simplified auxiliaries and control systems. The costs of the complete basic Stirling engine and most of the controls and auxiliaries were estimated in detail by Pioneer Engineering and Manufacturing Company (ref. 11). This RESD cost 25 percent less (table IV) and used 30 percent fewer major parts than the 1981 RESD. The Stirling engine, installed in a vehicle, appears to be competitive with Otto and diesel engines of similar power. Pioneer also analyzed various engines by using first costs and operating characteristics on a life-cycle basis. Their analysis (table V) shows the Stirling as an attractive alternative to the existing technologies. These results are presented in detail in reference 12.

PROJECT TRENDS

The trend charts (figs. 8 to 10) summarize overall progress and expectations in the program. As shown, strategic material content is being drastically reduced. Chromium content should be less than 0.2 lb/hp in the Mod II, and cobalt content is already at zero in the upgraded Mod I engine. Engine specific weight of the RESD is about the same as that of spark ignition and diesel engines. The Mod II is little heavier, primarily because it is difficult to remove excess weight from an experimental engine. Manufacturing cost projections show substantial improvements, with the RESD cost estimated to be midway between spark ignition and diesel engine costs. Substantial engine efficiency gains have been made, and the Mod II engine is expected to have a maximum brake efficiency near 40 percent. At the start of the program the vehicle fuel economy displayed with P-40 engines was well below that of spark ignition engine vehicles. Mod I and upgraded Mod I vehicles have shown significant improvement, and the Mod II engine in the Celebrity vehicle is expected to achieve its goal of at least 30 percent better fuel economy than the spark ignition Celebrity vehicle.

OUTLOOK FOR AUTOMOTIVE STIRLING ENGINES

Technically the program is progressing very well. Good progress has been made in the key technologies (i.e., rod seals, piston rings, controls, and materials). Engine performance is near predictions; experimental reliability has been good; and the MTBF has improved significantly. Although the fuel economy improvement goal is still a difficult, moving target, it is expected that it will be met by the Mod II engine in the Celebrity. Finally cost projections indicate the RESD to be cost competitive with spark ignition and diesel engines. Much development obviously remains to be done, particularly in achieving life goals. However, there are no major technology barriers that would bar the kinematic Stirling engine from commercial development.

Being an automobile engine program, its ultimate success would see Stirling engine automobiles in mass production. Discussions with U.S. automobile manufacturers indicate this will not occur unless the Stirling engine is first commercialized in a small "starter market" application. Such a starter market would reduce the risk by providing a solid commercial base of experience and establishing a credible basis for mass production cost estimates.

There are a number of such potential starter market applications where Stirling engines offer significant advantages and where, and in some cases, limited development is under way. These include engine-generator sets, heat pumps, irrigation pumping, automotive vans, submarines, solar terrestrial, and space power applications.

Key advantages of Stirling engines in these applications include "true" multifuel capability (including the potential for use of "broadcut" fuels and the elimination of octane or cetane requirements), high efficiency, low emissions (with no catalytic converter), low noise levels without a muffler, and the potential for lower maintenance costs (one ignitor, no catalytic convertor or particulate trap, no muffler, "no" oil changes, and "no" oil filter changes).

Thus the path to mass production of the Stirling engine automobile appears to lie through these other alternative, limited-production applications. This path will take more time, as a starter market application is developed, but it significantly improves the likelihood of ultimate program success - Stirling engine automobiles being manufactured in mass production.

REFERENCES

1. Beremand, D.G.: DOE/NASA Automotive Stirling Engine Project Overview '83. Energy for the Marketplace, 18th IECEC, AIChE, 1983, pp. 681-688.

2. Thieme, L.G.: High-Power Baseline and Motoring Test Results for the GPU-3 Stirling Engine. NASA TM-82646, 1981.

3. Kelm, G.G.; Cairelli, J.E.; and Walter, R.J.: Test Results and Facility Description for a 40-Kilowatt Stirling Engine. NASA TM-82620, 1981.

4. Haverdink, W.H.; Heffner, F.E.; and Amann, C.A.: Assessment of an Experimental Stirling-Engine-Powered Automobile. GMR-4817, General Motors Research Laboratories, Warren, MI, Aug. 1984.

5. Test and Evaluation of a Mod I Automotive Stirling Engine. JD-83-PEC9, Deere & Company, Government Products Operations, Moline, IL, Aug. 1985.

6. Shaltens, R.K.: Stirling Powered Van Program Overview. NASA TM-87227, 1986.

7. Titran, R.H.; and Stephens, J.R.: Advanced High Temperature Materials for the Energy Efficient Automotive Stirling Engine. J. Mater. Energy Systems, vol. 6, no. 2, 1984, pp. 114-121.

8. Stephens, J.R.; and Barrett, C.A.: Oxidation and Corrosion Resistance of Candidate Stirling Engine Heater-Head-Tube Alloys. NASA TM-83609, 1984.

9. Titran, R.H.; Stephens, J.R.; and Scheuermann, C.M.: Stirling Materials Technology. Proceedings of the Twenty-Second Automotive Technology Development Contractors' Coordination Meeting, SAE P-155, SAE, 1984, pp. 181-190.

10. Hulligan, D.D.; and Tomazic, W.A.: Effect of Water on Hydrogen Permeability. Proceedings of the Twenty-Second Automotive Technology Development Contractors' Coordination Meeting, SAE P-155, SAE, 1984, pp. 191-196.

11. Manufacturing Cost Analysis, RESD V-4, Mark V, 60 kW Stirling Engine. Pioneer Engineering & Manufacturing Company, Madison Hts., MI, July 1984.

12. Corey, J.; Khan, K.A.; and Kaminski, H.: Design Description of an Automotive Stirling Engine with a Competitive Manufacturing Cost. Proceedings of the Twenty-Second Automotive Technology Development Contractors' Coordination Meeting, SAE P-155, SAE, 1984, pp. 133-142.

TABLE I. - ENDURANCE OF MOD I ENGINE

[As of December 1985.]

Year	Engine	Endurance, hr	Duty cycle	Operating temperature, °C	Purpose
1984	6	1000	(a)	720	Materials
1984	7	2300	(b)		Seals
1985	7	1000	(a)		Seals
1985	7	1000	(a)		Seals
1985	6	2300	(a)	820	Materials

[a]Simulated EPA urban and highway driving cycle.
[b]Accelerated EPA urban and highway driving cycle.

TABLE II. - ENGINE MEAN TIME BETWEEN FAILURES FOR MOD I ENGINE

[As of December 1985.]

Engine	Total operating time, hr	Mean time between failure, hr
3	2023	112
5	1531	153
6	2711	387
7	4480	1120
8	1099	550
9	338	48
10	106	106

TABLE III. - BASELINE PERFORMANCE OF MOD II ENGINE

[Mod II in an 1985 Celebrity.]

Fuel economy, mpg:	
City	33.0
Highway	63.2
Combined	42.0
Acceleration 0 to 60 mph, sec	13.0
Emissions, g/mile:	
NO_x	<0.4
HC	<0.41
CO	<3.4
Particulates	<0.2
Key features:	
Power (maximum), kW (hp)	60 (80)
Height, mm (in.)	710 (28.0)
Width, mm (in.)	574 (22.6)
Weight, kg (lb)	203 (447.0)

TABLE IV. - COST OF 1983 RESD ENGINE

	Initial production cost, dollars	Mature cost, 1984 dollars
Total basic engine	808	687
Total controls and auxiliaries	707	627
Engine system total	1515	1314

TABLE V. - COMPARISON OF COSTS

	Stirling	Otto	Diesel
Total installed cost, dollars	2017	1802	2198
Total life-cycle cost, dollars	6705	7510	6770

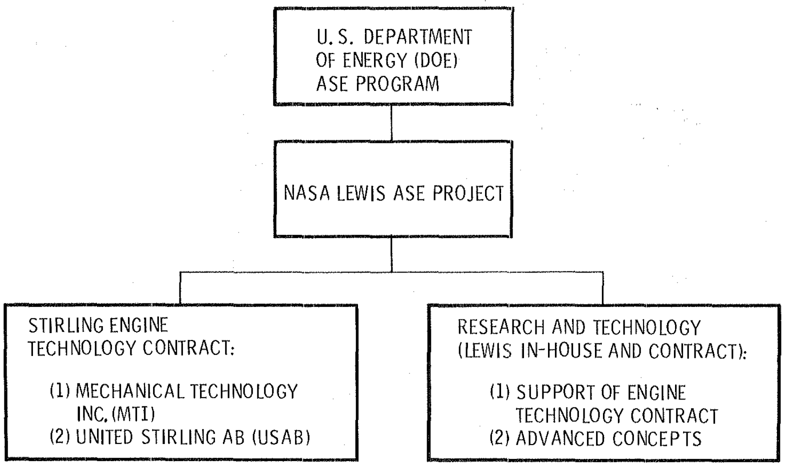


Figure 1. - Organization of Automotive Stirling Engine Project.

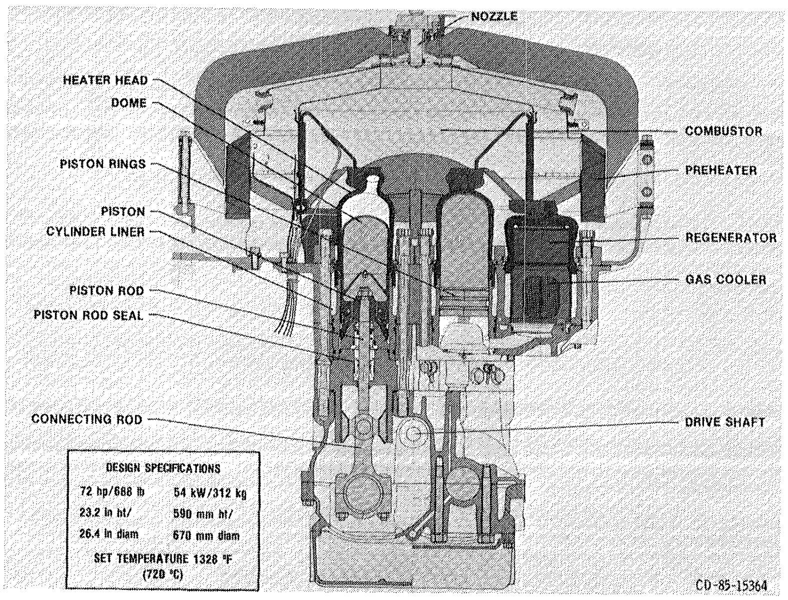


Figure 2. - Mod I automotive Stirling engine.

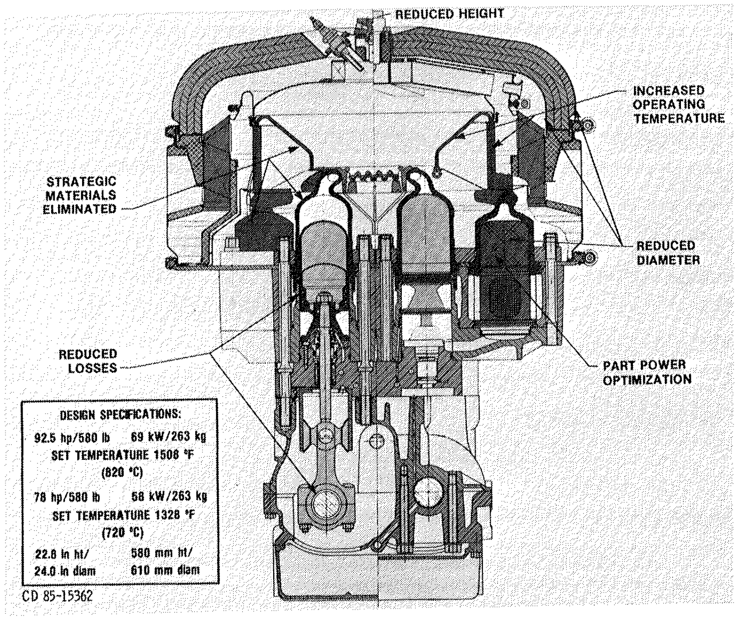


Figure 3. - Upgraded Mod I automotive Stirling engine.

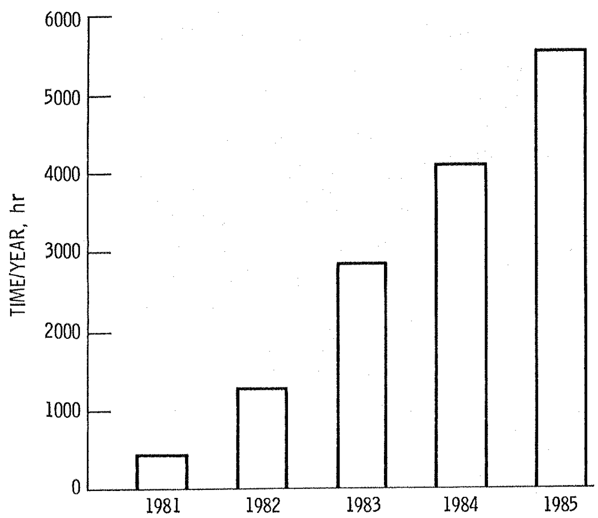


Figure 4. - Mod I engine test times (over 14 000 hr accumulated as of December 1985).

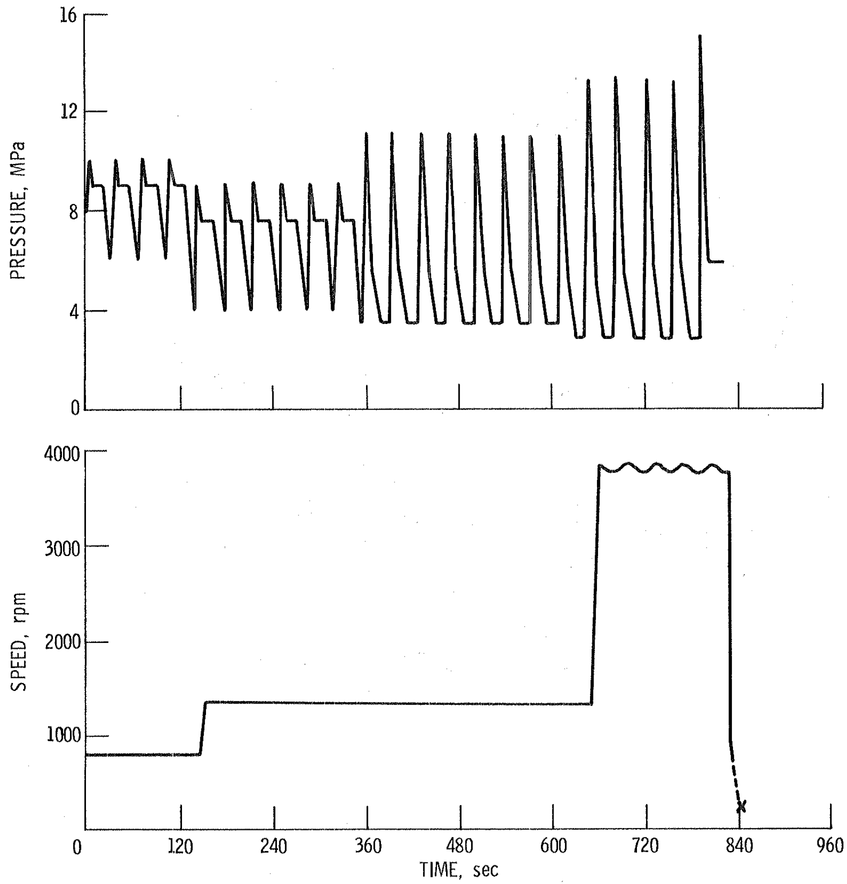


Figure 5. - Simulated EPA urban and highway driving cycle.

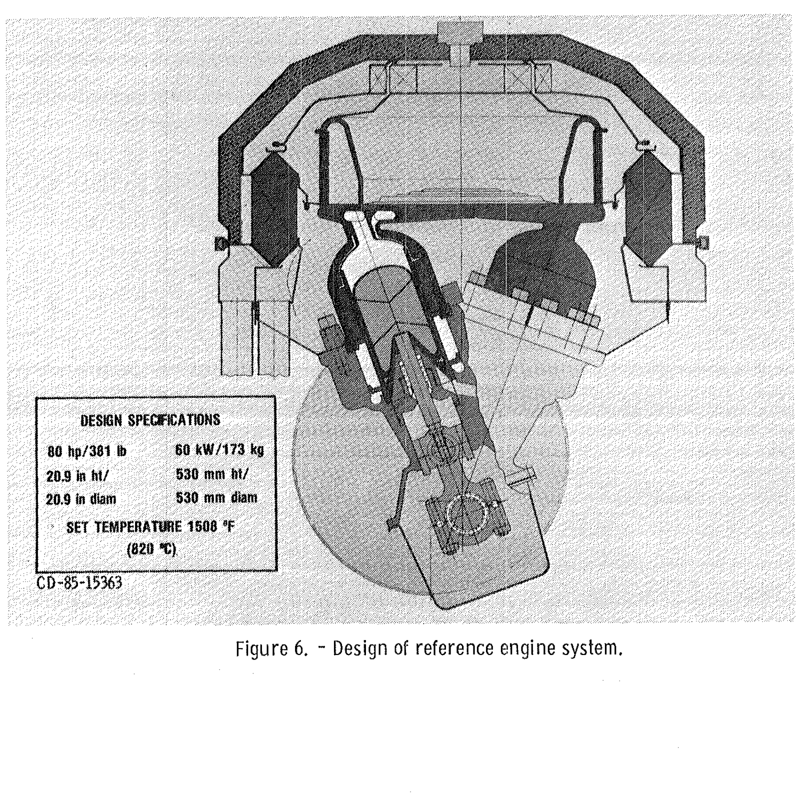


Figure 6. - Design of reference engine system.

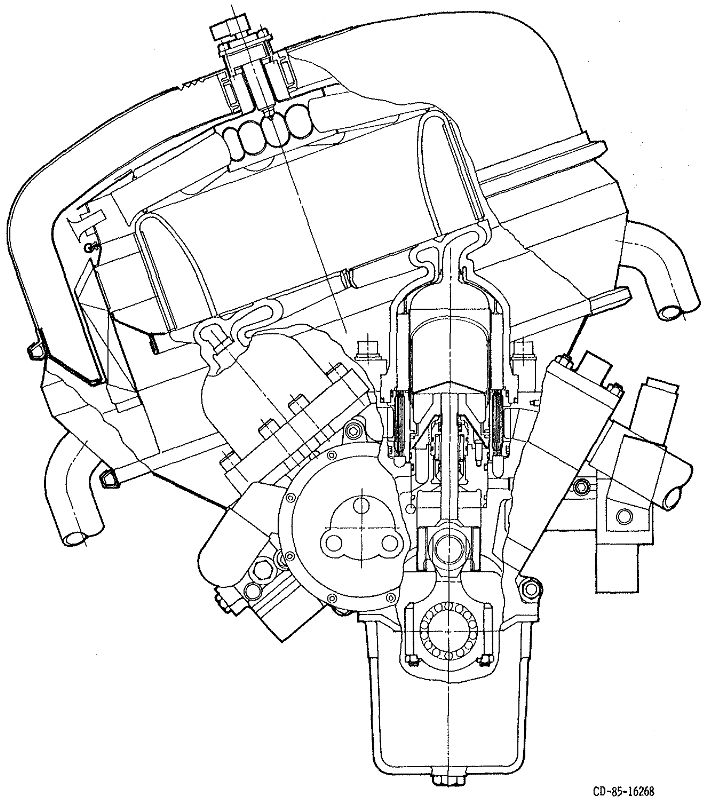
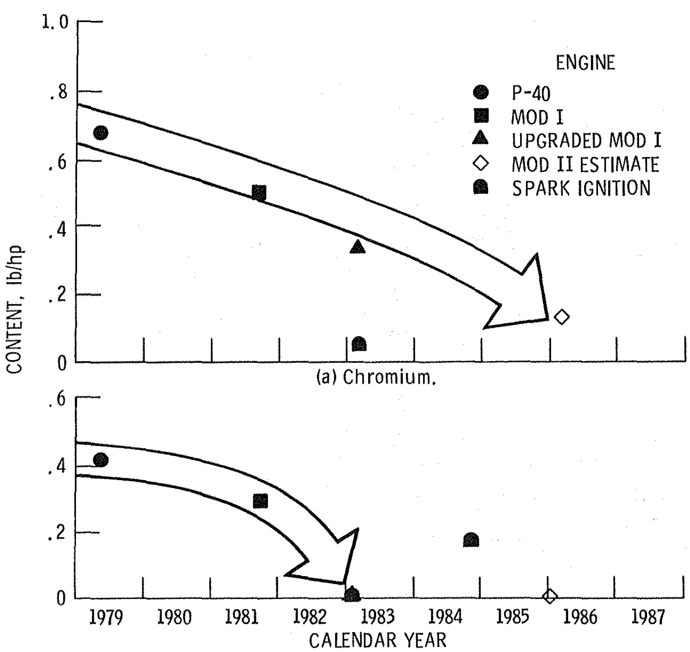
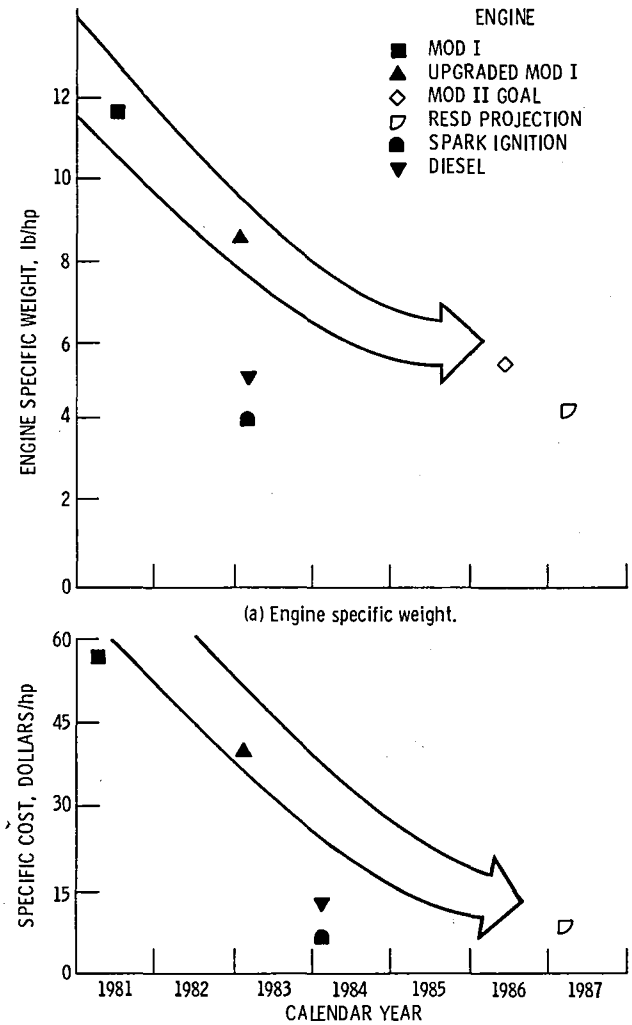


Figure 7. - Mod II automotive Stirling engine.



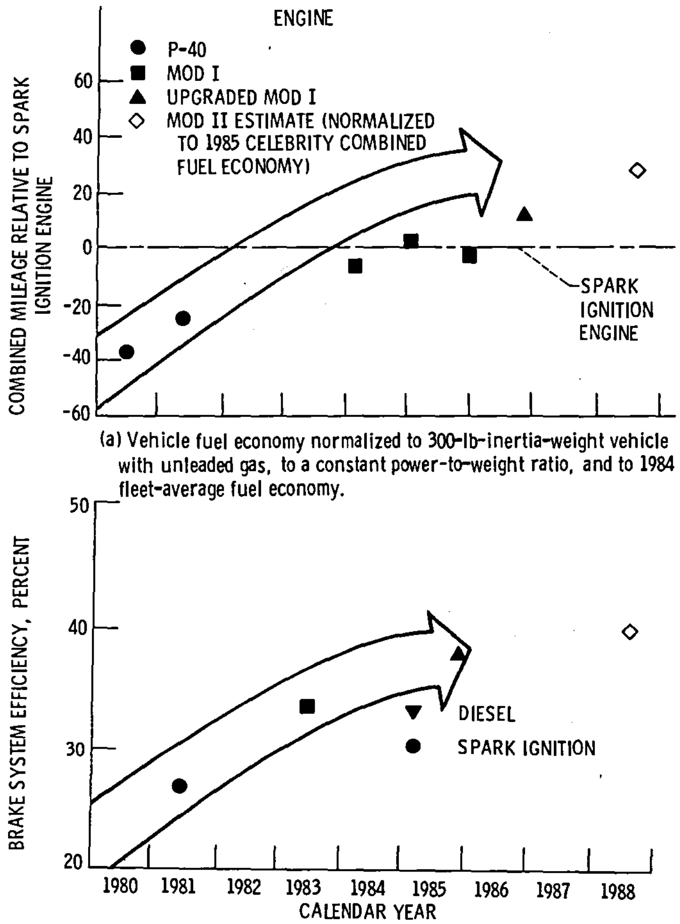
(b) Cobalt.

Figure 8. - Use of strategic materials in automotive Stirling engines.



(b) Manufacturing cost projection (1984 dollars).

Figure 9. - Specific weight and manufacturing cost projection for automotive Stirling engines.



(a) Vehicle fuel economy normalized to 300-lb-inertia-weight vehicle with unleaded gas, to a constant power-to-weight ratio, and to 1984 fleet-average fuel economy.

(b) Engine peak efficiency.

Figure 10. - Vehicle fuel economy and engine peak efficiency projection for automotive Stirling engines.

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16. Abstract

The DOE/NASA Automotive Stirling Engine Project is reviewed and its technical progress and status are presented. Key technologies in materials, seals, and piston rings are progressing well. Seven first-generation engines, and modifications thereto, have accumulated over 15 000 hr of test time, including 1100 hr of in-vehicle testing. Results indicate good progress toward the program goals. The first second-generation engine is now undergoing initial testing. It is expected that the program goal of a 30-percent improvement in fuel economy will be achieved in tests of a second-generation engine in a Celebrity vehicle.

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